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Magnetic ionic liquids based on transition metal complexes with N-alkylimidazole ligands

Abstract

In this study, magnetic ionic liquids (MILs) consisting of Ni(II), Co(II), and Mn(II) and paired with the bis[(trifluoromethyl)sulfonyl]imide [NTf₂⁻] anion were synthesized from their water soluble chloride intermediates. The MILs feature low viscosity, high hydrophobicity, and hydrolytic stability making them attractive candidates for a number of highly interdisciplinary applications.

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Magnetic Ionic Liquids Based On Transition-metal Complexes with N-Alkylimidazole Ligands

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In this study, magnetic ionic liquids (MILs) consisting of Ni(II), Co(II), and Mn(II) and paired with the bis[(trifluoromethyl)sulfonyl]imide [NTf₂]⁻ anion were synthesized from their water soluble chloride intermediates. The MILs feature low viscosity, high hydrophobicity, and hydrolytic stability making them attractive candidates for a number of highly interdisciplinary applications.

Introduction

Ionic liquids (ILs) are salts possessing a wide liquid range from cryogenic temperatures up to 100 °C. ILs are often composed of large asymmetric cations and anions, and can be designed for specific applications through the choice of the respective cation and anion combination.¹ In addition to their wide liquid range and the tunability of physicochemical properties, they have garnered significant attention due to their negligible vapor pressure, high thermal and chemical stability, wide electrochemical window, and unique solvation capabilities.²

MILs are a subclass of ILs that originate by incorporating high-spin transition metals and rare earth metals into their structure. MILs combine the properties of ionic liquids with magnetic, optical or catalytic properties that originate from the metal incorporated in the complex anion.^{3–6} MILs have been exploited in a wide range of applications including catalysis,^{7,8} fabrication of nanostructured and reduced dimensionality materials such as thin films, tubes, wires or particles,⁹ electrochemical and medical devices;¹⁰ and in numerous analytical applications including liquid–liquid extractions (LLE) and stationary phases for gas chromatography (GC).^{11–14}

Heavily alkylated phosphonium cations and weakly-coordinating fluorinated anions such as

bis[(trifluoromethyl)sulfonyl]imide [NTf₂]⁻ are often employed to impart hydrophobicity to MILs.¹⁵ The majority of MILs contain anionic metal centers where the hydrophobicity is typically imparted through the inclusion of nonpolar moieties in the cation.¹⁶ Metallocenium ionic liquids containing a cationic metal center paired with weakly-coordinating [NTf₂]⁻ anions are generally less viscous.¹⁷ However, they are prone to hydrolysis because of the hydrolytic instability of the employed ligands used, which often limits their applicability.^{18,19} Ligands that possess better water stability can be helpful in improving the hydrolytic stability in the case of MILs containing cationic metal centers. Imidazole-based ligands, in combination with other auxiliary ligands that coordinate to the metal center, have been shown to produce MILs with good hydrolytic stability.²⁰

The magnetic susceptibility of MILs can be largely tuned for a specific application by incorporating different paramagnetic metals into the chemical structure.^{21–23} Mn(II) based MILs possess higher magnetic susceptibilities than Co(II) and Ni(II) MILs. Moreover, Mn(II) is known to exhibit interesting photophysical properties such as photoluminescence (fluorescence and phosphorescence),²⁴ triboluminescence²⁵ as well as electroluminescence.²⁶

In this study, we report the efficient synthesis of low viscosity and hydrophobic MILs based on Ni(II), Mn(II) and Co(II) that feature only imidazole ligands and the [NTf₂]⁻ anion. SQUID measurements provide insight into their magnetic behavior and the thermal properties of each MIL were evaluated using thermal gravimetric (TG) analysis and differential scanning calorimetry (DSC). Viscosity measurements revealed that MILs possessing 1-octylimidazole ligands are significantly less viscous (η = 152 cP). This study is likely to open up many new areas of opportunity in the fields of chemical separations, optoelectronics, electrochemistry, among others.

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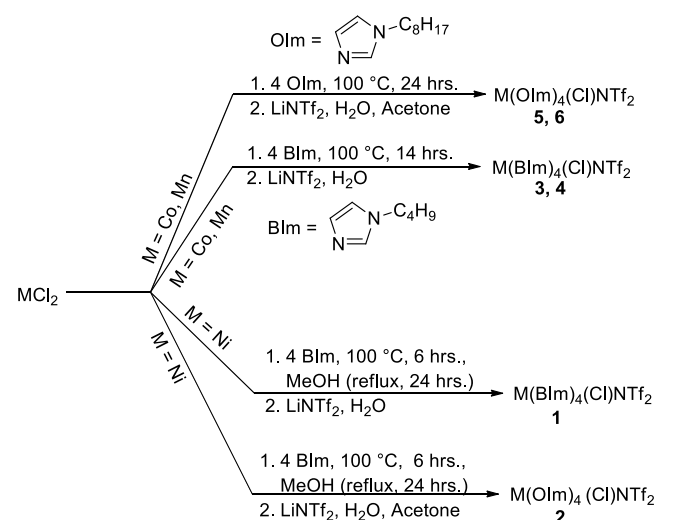
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Results and Discussion

Synthesis



Scheme 1. Synthesis of Ni(II), Co(II), and Mn(II) bis[(trifluoromethyl)sulfonyl]imide (NTf₂) based MILs and their chloride intermediates from anhydrous metal chlorides and 1-octylimidazole (Olm) and 1-butylimidazole (Blm) ligands.

Transition metal (Ni(II), Co(II), and Mn(II)) MILs were synthesized according to Scheme 1. The precursor chloride-based MILs were obtained in a solvent free reaction by treating the anhydrous metal chlorides with 1-butylimidazole (Blm) or 1-octylimidazole (Olm). The obtained MILs, in chloride form, were then treated with an aqueous solution of lithium bis[(trifluoromethyl)sulfonyl]imide to obtain the corresponding [NTf₂]-based MILs (1–6) via metathesis reaction. Detailed synthetic methods as well as elemental analysis, Raman, and IR spectroscopy data are provided in ESI.

Thermal Properties

The thermal properties of all [NTf₂]-based compounds were investigated by differential scanning calorimetry (DSC) and thermogravimetric (TG) analysis. Thermal data are summarized in Table 1. All synthesized [NTf₂]-based MILs have moderate thermal stability ranging from 149 – 178 °C and decompose in a

Table 1. Thermal properties of the MILs 1–6 obtained from DSC and TGA measurements

MIL	Abbreviation	Physical State at Room Temperature (RT), 25 °C	Melting Point [°C]	Decomposition Temperature [°C]
1	Ni(Blm) ₄ (Cl)NTf ₂	Solid	65.8	164
2	Ni(Olm) ₄ (Cl)NTf ₂	Liquid	< 25	178
3	Co(Blm) ₄ (Cl)NTf ₂	Solid	< 40	159
4	Mn(Blm) ₄ (Cl)NTf ₂	Solid	< 40	149
5	Co(Olm) ₄ (Cl)NTf ₂	Liquid	< 25	168
6	Mn(Olm) ₄ (Cl)NTf ₂	Liquid	< 25	168

two-step thermal pathway (see ESI). The MILs composed of octylimidazole ligands appear to have slightly better thermal stability than their 1-butylimidazole counterparts. The identity of gases evolved during the heating process was determined by mass spectrometry detection and shows that fluorinated hydrocarbons are the major decomposition products (see ESI). Therefore, the thermal stability of these ionic liquids is limited by the strength of metal – heteroatom bond, otherwise [NTf₂]-based ILs generally have very good thermal stability.^{27,28}

Viscosity

Table 2. Viscosity and solubility data of the MILs synthesized in this study

MIL	Abbreviation	Viscosity ^a [cP]	Solubility
1	Ni(Blm) ₄ (Cl)NTf ₂	2501 ^e	I ^b , S ^{c,d}
2	Ni(Olm) ₄ (Cl)NTf ₂	680	I ^b , S ^c
3	Co(Blm) ₄ (Cl)NTf ₂	1256 ^e	I ^b , S ^{c,d}
4	Mn(Blm) ₄ (Cl)NTf ₂	1245 ^e	I ^b , S ^{c,d}
5	Co(Olm) ₄ (Cl)NTf ₂	152	I ^b , S ^c
6	Mn(Olm) ₄ (Cl)NTf ₂	303	I ^b , S ^c

^aViscosity measurements were performed at 21.7 °C; additional details are provided in Supporting Information. I^b = insoluble in hexane at 0.01% (w/v) and insoluble in water at 0.001% (w/v) MIL to solvent ratio. S^c = Soluble in acetone, acetonitrile, chloroform, dichloromethane, ethanol, ethyl acetate, methanol at 0.01% (w/v) MIL to solvent ratio. S^d = 50 % soluble in toluene and diethyl ether at 0.01% (w/v) MIL to solvent ratio (v/v) MIL to solvent ratio. ^eThe viscosity of the MILs was measured after synthesis/purification. Over time, the Blm-based MILs formed solids (see Table 1).

MILs of low viscosity are desirable in applications such as liquid–liquid extraction (LLE),²⁹ electrodeposition of metals,³⁰ and in the design of equipment such as heat exchangers.^{31,32} For MILs that contain an anionic metal center, hydrogen bonding and van der Waals interactions are often the limiting factors that determine viscosity.³³ The viscosity has been found to generally increase with an increase in alkyl chain length for MILs containing the 1-alkyl-3-methylimidazolium cation.³⁴ Viscosities of MILs 1–6 are presented in Table 2. It can be seen that the viscosity decreases with an increase in carbon chain length of the imidazole ligand. MILs with 1-octylimidazole ligands are significantly less viscous than MILs comprised of 1-butylimidazole ligands. The Co(Olm)₄(Cl)NTf₂ MIL exhibited a viscosity of 152 cP at 21.7 °C and is the least viscous among the synthesized MILs in this study. MILs 1, 3 and 4 are highly viscous liquids and were observed to solidify when stored for extended periods of time at room temperature. Therefore, these MILs, and in particular those with octyl-imidazole ligands, are less viscous than previous generations of MILs. For example, the viscosity of phosphonium metal halide based MILs is on the order of 100,000 cP,³⁵ while the viscosities of phosphonium metal-diketonate MILs range between 400–1000 cP.¹⁶

The solubility data presented in Table 2 shows that, independent of the nature of the ligand, MILs 1–6 were immiscible with water at compositions as low as 0.001% (w/v) MIL-to-solvent ratio. Despite their hydrophobic nature, these MILs are insoluble in nonpolar solvents such as hexane at 0.01%

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(w/v) MIL-to-solvent ratio. Therefore, the hydrophobic properties of these MILs are ideal for applications such as aqueous liquid–liquid microextractions, where extremely low phase ratios of extraction solvent are employed; photoluminescent materials,³⁶ where water could quench the luminescence due to vibronic coupling and magnetic ionic liquid membranes for gas separations.³⁵ MILs bearing the 1-butylimidazole ligand, (e.g., Ni(BIm)₄(Cl)NTf₂, Co(BIm)₄(Cl)NTf₂, and Mn(BIm)₄(Cl)NTf₂), were found to be partially soluble in toluene and diethyl ether. All of the reported MILs dissolved completely in higher polarity solvents such as acetone, acetonitrile, chloroform, dichloromethane, ethanol, ethyl acetate, and methanol.

Magnetic Properties

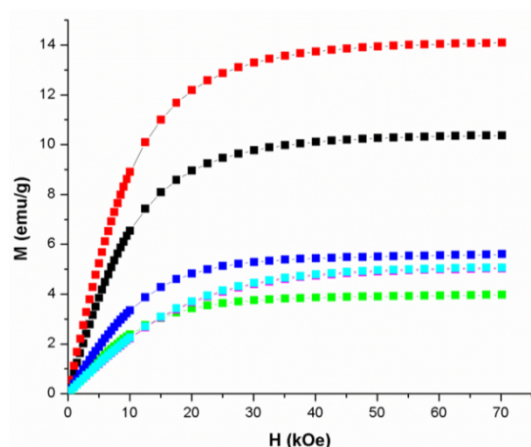


Figure 1. Magnetization of MILs 1–6 as a function of applied magnetic field at $T = 2$ K, Mn(OIm)₄(Cl)NTf₂ (red), Mn(BIm)₄(Cl)NTf₂ (black), Co(BIm)₄(Cl)NTf₂ (green), Co(OIm)₄(Cl)NTf₂ (dark blue), Ni(BIm)₄(Cl)NTf₂ (pink), Ni(OIm)₄(Cl)NTf₂ (light blue).

Magnetic properties were measured using a Quantum Design MPMS SQUID magnetometer in the temperature range of 2–300 K with an external magnetic field as high as 70 kOe. The magnetization of MILs 1–6, measured at 2 K as a function of applied magnetic field, show a tendency of saturation which is typical for ferromagnetic behavior (Figure 1); however, the magnetization values are rather small. The observation that these MILs can be manipulated by a hand-held neodymium magnet also confirms their magnetic nature.

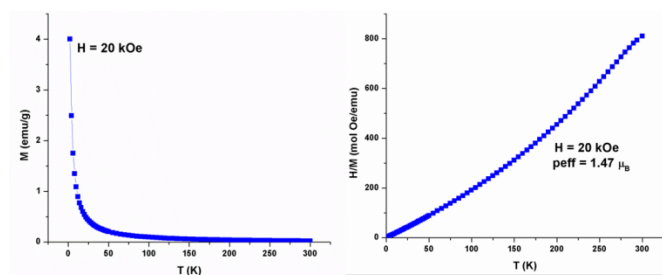


Figure 2. Magnetization of the Ni(OIm)₄(Cl)NTf₂ MIL measured as a function of temperature at $H = 20$ kOe (left). The Curie-Weiss fit of the linear portion of the reciprocal susceptibility is shown at the right.

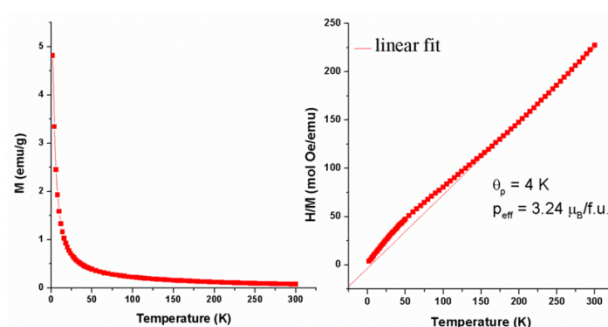


Figure 3. Magnetization vs temperature plot for the Co(OIm)₄(Cl)NTf₂ MIL (left) at $H = 20$ kOe and Curie-Weiss fit of the linear portion of the reciprocal susceptibility (right)

Figure S17 and videos provided as *Supporting Information* show manipulation of the MILs using a 0.66 T handheld magnet. Fig. 2 shows the temperature dependence of magnetization and a plot of the reciprocal susceptibility versus temperature for the Ni(OIm)₄(Cl)NTf₂ (2) MIL, confirming an inverse relationship between magnetic susceptibility and temperature as defined by the Curie–Weiss law. The calculated μ_{eff} for the Ni(OIm)₄(Cl)NTf₂ MIL was $1.47 \mu_{\text{B}}$ which indicates that the compound exists in an equilibrium state between square planar (no unpaired electron) – tetrahedral (two unpaired electrons) because of the noncoordinating nature of the [NTf₂][−] anions.^{37–38} Similar magnetic behaviour has been observed for the Ni(BIm)₄(Cl)NTf₂ MIL (see *Supporting Information*).

Similarly, Co(OIm)₄(Cl)NTf₂ (5) and Mn(OIm)₄(Cl)NTf₂ (6) exhibit normal paramagnetic behavior, as shown in Figure 3 and Figure S15 (*Supporting Information*), respectively. The calculated μ_{eff} for 5 and 6 were 3.24 and $4.04 \mu_{\text{B}}$, respectively. Plots of magnetization versus temperature and reciprocal molar susceptibility versus temperature for MILs 1, 3 and 4 are reported in the supporting information. It can be observed that Co(BIm)₄(Cl)NTf₂ (3) displays a phase transition above 270 K. The magnetic susceptibility values of MILs 1–6 are 0.31, 0.37, 0.78, 2.55, 1.32, and 2.17 emu K mol^{−1}, respectively, while the reported values for (P₆₆₆₁₄)₂CoCl₄ and (P₆₆₆₁₄)₂MnCl₄ are 2.10 and 4.23 emu K mol^{−1}, respectively.¹⁵ These lower magnetic susceptibilities could be the result of an equilibrium between the square planar and tetrahedral geometries for the [NTf₂][−]-based MILs.

Conclusions

MILs comprised of the [NTf₂][−] anion and cations based on transition-metal complexes with 1-alkylimidazole ligands were prepared using an efficient synthetic methodology involving the solvent free synthesis of chloride intermediates. The metal containing chloride intermediates were found to be stable in water and were converted into their [NTf₂][−] form through a simple metathesis reaction pathway. The resulting MILs were found to be hydrophobic and significantly less viscous, especially for those bearing 1-octylimidazole ligands. Co(OIm)₄(Cl)NTf₂ was found to be the least viscous MIL with a viscosity of 152 cP at 21.7 °C. SQUID magnetic measurements performed on the reported ionic liquids confirm their magnetic

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nature. These MILs exhibit moderate thermal stability and are expected to be useful new materials in diverse areas of catalysis, chemical separations, and opto-electronics.

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Conflicts of interest

The authors declare no conflicts

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Graphical Abstract:

Nickel(II), cobalt(II) and manganese(II) N-alkylimidazole bis[(trifluoromethyl)sulfonyl]imide magnetic ionic liquids were synthesized from their chloride intermediates and their physicochemical properties studied.

